NASA Technical Memorandum 113130

The Effect of Spaceflight on the Critical Current Density of $YBa_2Cu_3O_{7-x}$ Thick Films

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Abstract

Screen-printed thick films of the $YBa_2Cu_3O_{7-x}$ high-temperature superconductor were integrated into hybrid microelectronics circuits and characterized on orbit as part of the Materials In Devices As Superconductors (MIDAS) spaceflight experiment. The experiment operated autonomously for 90 days on the Mir space station and acquired electrical data on the superconductive films at temperatures ranging from 250 to 75K. This report describes the on-orbit critical current density, J_c, performance of the $YBa_2Cu_3O_{7-x}$ thick films and compares the flight data with those obtained during pre- and post-flight testing. The results of this investigation show no significant difference between the spaceflight and ground data, indicating that no degradation occurred in the superconductive films due to either vibrational loads experienced during launch or continuous operation in a microgravity environment.

Introduction

High-temperature superconductors have been proposed for use in several spacecraft systems due to their unique electrical, magnetic, and thermal properties (refs. 1-3). In each instance, the replacement of existing materials with high-temperature superconductors would either significantly increase the performance capability of the spacecraft instrument or substantially reduce the payload size and weight, thereby reducing launch costs. Furthermore, several spacecraft already employ cryogenic refrigeration systems, providing an operational environment well-suited for the use of superconductive devices.

Thick films of the high-temperature superconductive materials have been successfully fabricated using conventional manufacturing processes such as screen printing. These films have been deposited onto polycrystalline ceramic substrates such as Al_2O_3 and ZrO_2 and have been found to exhibit critical current density, J_c, values up to 100 A/cm^2 (refs. 4-6). Although the J_c properties of these films are lower than those of preferentially-oriented thin films of the same materials, the thick films do exhibit sufficient performance characteristics for many aerospace applications (refs. 1 and 3). Additionally, these films can be produced using low cost manufacturing methods and commonly used processing techniques. Finally, these films can be integrated with conventional microelectronics circuitry to create unique devices for a variety of applications. Recently, researchers at NASA-Langley Research Center (LaRC) have demonstrated hybrid circuits containing superconductive thick films, multilayer insulators and conductors, and surface-mounted electronic components in a single active microelectronics package (ref. 7).

However, despite the recent advances in film processing and integration and the high potential for space applications of superconductive materials, concerns do exist regarding the survivability of these materials under launch vibrations and their long term performance in a microgravity environment. To address these concerns, the Materials In Devices As Superconductors (MIDAS) experiment was developed. The experiment was designed to operate autonomously on the Mir space station and acquire electrical data on superconductive film specimens at temperatures ranging from 250 to 75K. The experiment was launched on Space Transportation System mission 79 (STS-79) in September of 1996 and transferred to the Priroda module of the Mir. The experiment operated for 90 days aboard the Mir and automatically shut down prior to its return to Earth on STS-81 in January of 1997.

Twenty-four thin and thick film high-temperature superconductive specimens of various compositions and sources were flown on the MIDAS experiment. This report addresses the critical current density properties of the twelve $YBa_2Cu_3O_{7-x}$ thick films fabricated at LaRC. Additionally, the flight data are compared to the data collected during pre- and post-flight operations of the experiment. The resistance versus temperature characteristics of the thick films have been reported elsewhere (ref. 8). Data on the thin film specimens will be published separately.

Experimental Procedure

Thick Film Specimens

The superconductive thick films employed in the MIDAS experiment were deposited using a screen-printing process. Powders of the $YBa_2Cu_3O_{7-x}$ superconductor were mixed with an organic binder and printed onto polycrystalline yttria-stabilized zirconia (YSZ) substrates using a 200-mesh screen patterned by photolithography. The resulting films were dried at 200ºC and then sintered for 30 minutes at 950ºC in air. During cooling, an oxygen atmosphere was introduced into the furnace, and the films were annealed at 600ºC for 3 hours to allow the oxygen content of the films to equilibrate. The details regarding the sintering of the superconductive films have been reported by Hooker, et al. (ref. 9).

The MIDAS test specimens were divided into groups of six for measurement. To produce a set of test specimens, six films with dimensions of 1.02 x 0.10 cm were deposited on a 2.54- x 2.54-cm YSZ substrate and sintered in the previously described manner. Gold conductive paths for connection to the measurement circuitry and four silver electrical contacts per superconductive film were then deposited using electron-beam evaporation.

A pre-fabricated measurement circuit designed to perform d.c. four-probe resistance measurements on the films was then prepared. The measurement circuit was fabricated on a 2.54- x 1.27-cm alumina substrate using conventional multilayer thick film processing. Three active electronic components were contained on the circuit, namely two multiplexers and an amplifier. The multilayer measurement circuit was adhesively bonded to the YSZ substrate, and the gold conductive paths to the superconductors were electrically connected by wire bonds. A photograph showing both a YSZ substrate containing six superconductive films and electrical paths and an integrated hybrid circuit is provided in figure 1.

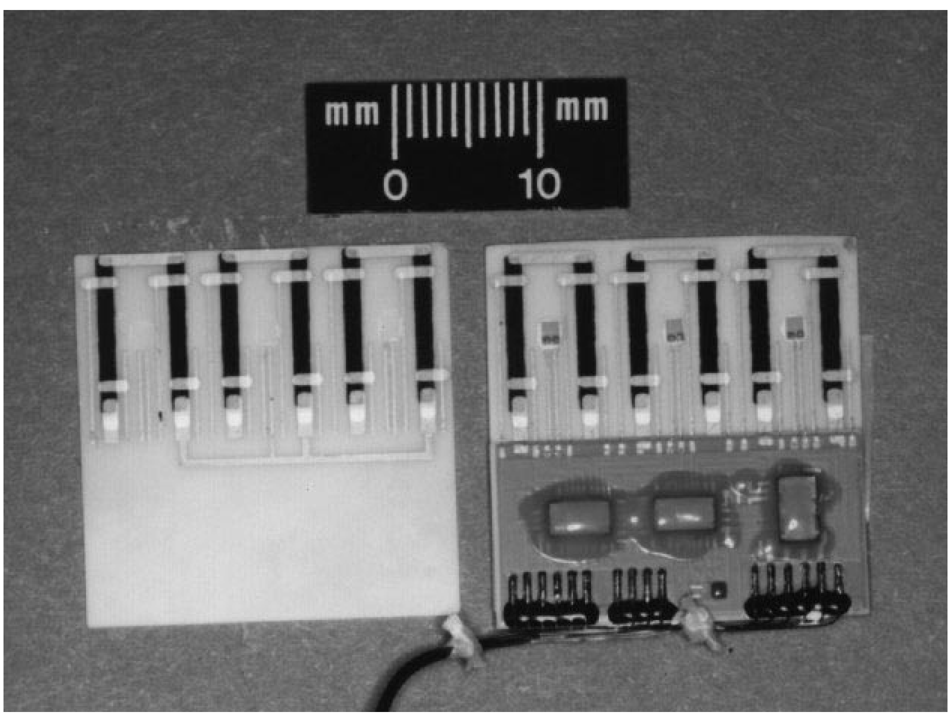

Figure 1. Photograph showing the superconductive thick films, silver electrical contacts, and gold conductive paths deposited on a YSZ substrate (left) and the integrated hybrid circuit (right).

Four Platinum Resistive Thermometer (PRT) temperature sensors were located on each hybrid circuit to accurately monitor the circuit temperature during testing. Three sensors were located among the superconductive films, while the fourth sensor was placed near the electronic components to determine the extent of self-heating during operation. A photograph of one of the fully integrated MIDAS test circuits is provided in figure 2. Two hybrid circuits, each containing six $YBa_2Cu_3O_{7-x}$ films, were flown on the MIDAS experiment. Each circuit and specimen were assigned unique nomenclature for data recording. The thick film circuits were referred to as circuits 1 and 3 (C1 and C3), and each circuit possessed six superconductive films (S1-S6). Hence, the first specimen on circuit 1 was referred to as C1, S1.

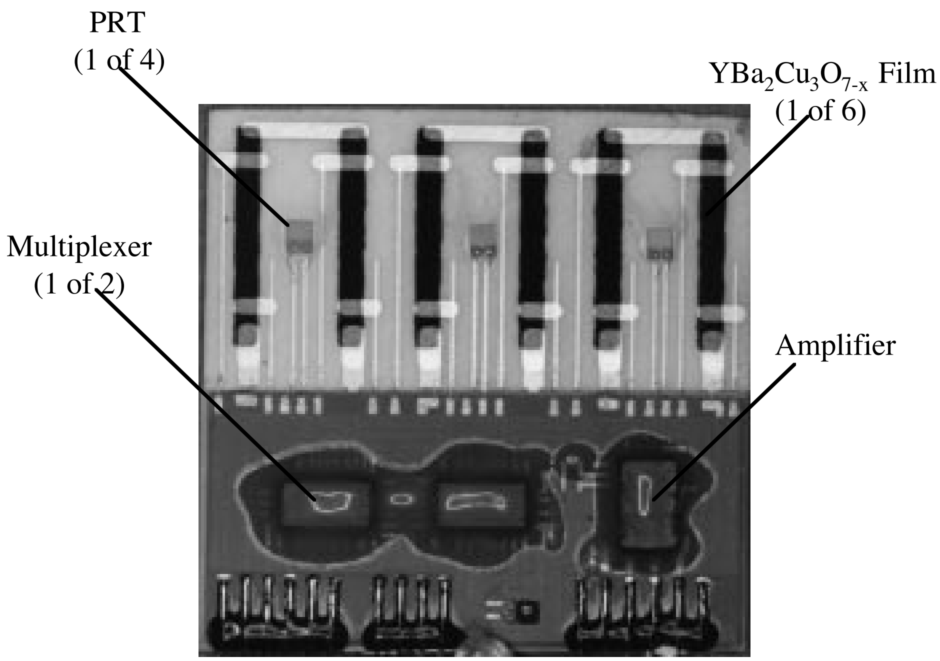

Figure 2. Fully integrated hybrid test circuit used in the MIDAS experiment.

MIDAS Hardware

The MIDAS experiment was designed and constructed to accomplish on-orbit electrical measurements of superconductive films at temperatures ranging from 250 to 75K. To meet these objectives, the MIDAS hardware consisted of three major subsystems as follows: (1) the superconductor specimens resident on hybrid circuits fabricated as previously described; (2) a vacuum chamber, ion pump, and cryocooler for controlling the specimen temperature; and (3) a data acquisition system capable of supplying current to the films, acquiring voltage outputs, and storing the data gathered. A schematic of the MIDAS experiment illustrating the primary hardware components is provided in figure 3. A comprehensive description of the flight hardware has been given by Amundsen, et al. (ref. 10).

The four measurement circuits were bonded to the primary surfaces of a hollow copper cube and mounted inside the vacuum chamber. To avoid damaging the cryocooler cold finger, the cube was attached to a titanium structural support and thermally connected to the cold finger via a copper strap. A photograph showing the mounting configuration for the superconductive specimens inside the vacuum chamber is provided in figure 4. The vacuum chamber was sealed and evacuated prior to spaceflight. An ion pump was used during the experiment to maintain the necessary vacuum level for optimum cryocooler performance.

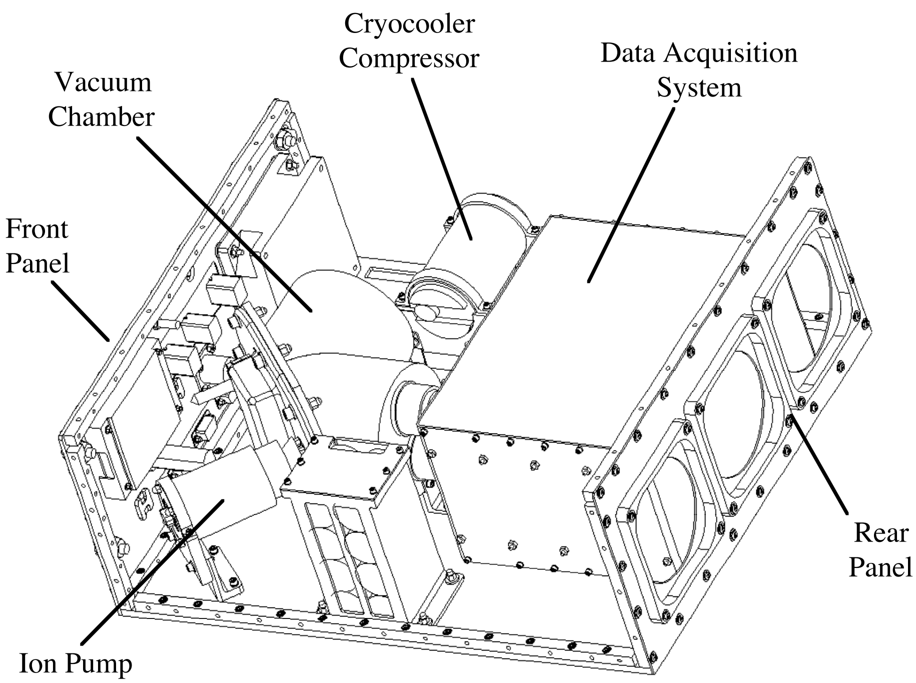

Figure 3. Schematic of the MIDAS experiment showing the major subsystem components (with top cover removed).

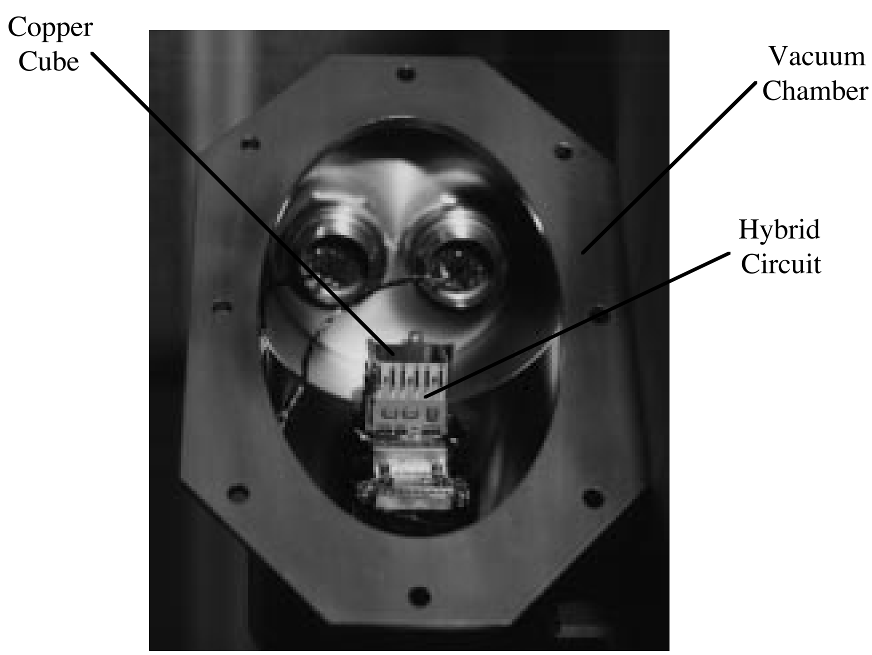

Figure 4. Photograph of the superconductive films mounted inside the MIDAS vacuum chamber.

Measurements Performed

The timing of the experiment was accomplished using a programmed measurement schedule. Once the experiment was initiated on the Mir, the cryocooler began cooling the superconductive specimens from ambient to 75K. During cool-down, the resistance versus temperature properties of each specimen were measured in order to define the critical transition temperature, T_c. Once 75K was attained, the current versus voltage characteristics of each specimen were measured every 30 minutes to evaluate the J_c properties. After a period of 28 days at 75K, the specimens were warmed to room temperature, and resistance versus temperature data were again obtained. After a 48-hour inactive period to allow the cryocooler to equilibrate, the measurement cycle was repeated. Three 30-day iterations of this cycle were completed on orbit, resulting in approximately 4000 J_c measurements per specimen.

The electrical measurements were performed by directing positive and negative currents of equal magnitude (e.g., +0.1 and -0.1 mA) to the outer contacts of each superconductive film. The absolute values of the voltages generated at the two inner contacts were then acquired and averaged. The J_c measurements were accomplished by applying current in 0.1 mA increments and monitoring the voltage generated. The films were considered superconductive when the voltage output was less than 0.01 mV. The critical current density, J_c, for each specimen was calculated by dividing the critical current (i.e., the highest current at which the voltage output was less than 0.01 mV) by the cross-sectional area of the film (i.e., 0.00025 cm^2).

Experimental Results

While aboard the Mir space station, the MIDAS experiment initially cooled the circuits to approximately 75K over a six-hour period. However, after fourteen hours, a hardware anomaly occurred in which the ion pump used to maintain the pressure level inside the vacuum chamber became inoperative. Without the ion pump operating, the pressure level in the vacuum chamber began to rise, resulting in a subsequent increase in specimen temperature. The specimens warmed to 95K over a 4-day period and continued to warm to approximately 120K over the remainder of the 28-day cycle. During both the second and third iterations of the measurement cycle, the specimens reached a minimum temperature of approximately 125K, and the temperature remained relatively constant throughout each 28-day period. Although all data were acquired according to the timed measurement schedule, the specimens were only maintained below the superconductive transition temperature for the first few days of the experiment. Figures 5a and 5b illustrate the temperature of the cryocooler cold finger during the first and second iterations of the experiment respectively. The temperature of the cryocooler cold finger during the third iteration closely approximates the second iteration shown in figure 5b.

Although the planned minimum temperatures were not maintained throughout the 90-day duration, the critical current density of each thick film specimen was successfully measured on orbit during the first iteration of the experiment. The J_c values for the twelve specimens ranged from 1 to 24 A/cm^2 when measured at approximately 75K. Graphs of the current density versus voltage for the six specimens on circuits 1 and 3 are shown in figures 6a and 6b respectively. The on-orbit J_c values are comparable to the values obtained for the thick film specimens prior to launch. Figure 7 shows a comparison between the pre-flight and on-orbit data for a typical thick film specimen, indicating excellent agreement in the J_c properties of the films when tested on the ground and in space.

As anticipated, the J_c properties of the thick film specimens were found to be highly dependent on the film temperature during measurement. As a result of the ion pump becoming inoperable after fourteen hours of on-orbit operation, the film temperature slowly increased during the first four days of the experiment. As the temperature approached T_c (87K), the J_c decreased significantly. Figure 8 illustrates the effects of temperature on the J_c properties of a typical thick film specimen when evaluated from 75 to 87K.

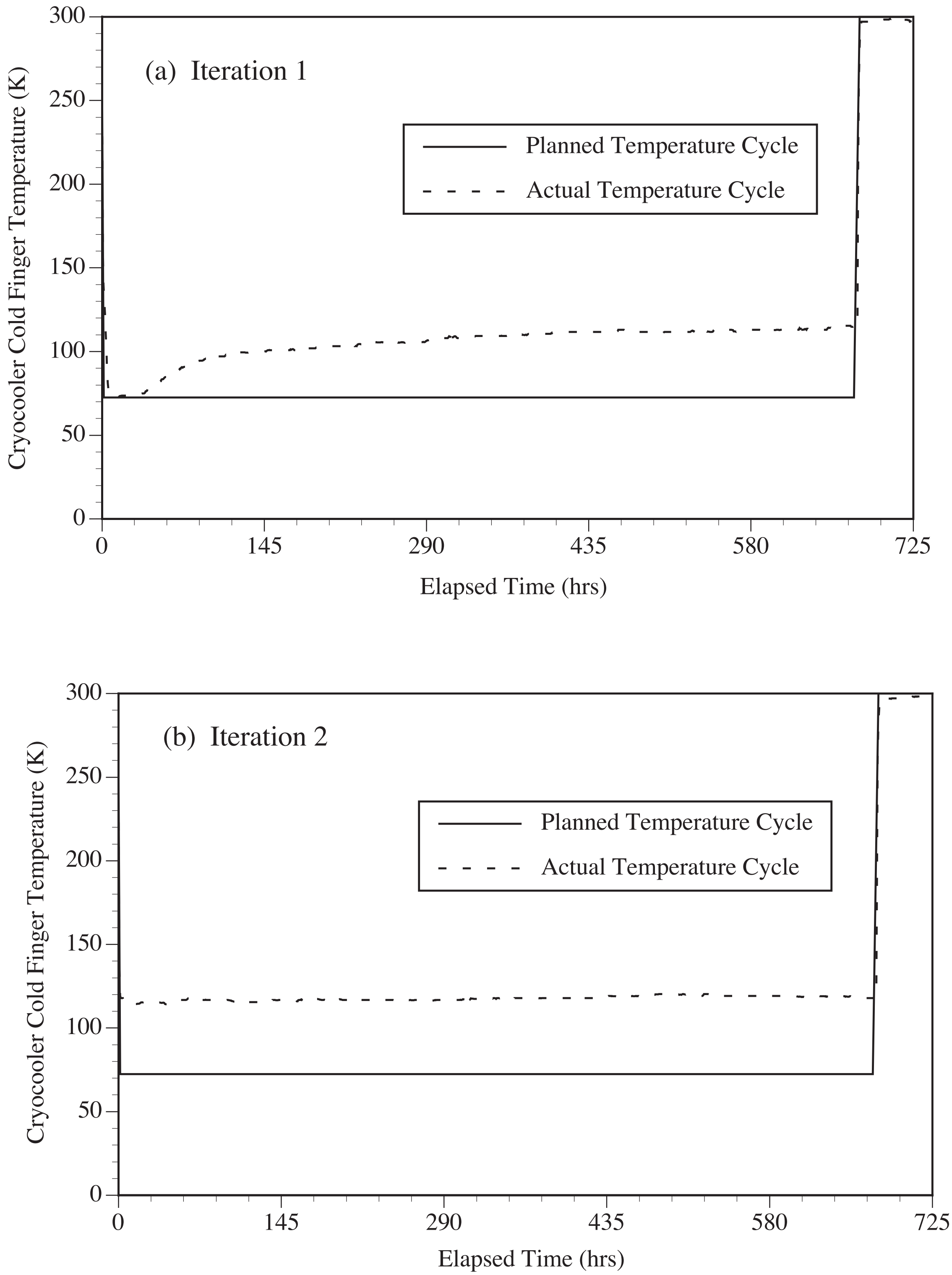

Figure 5. Cryocooler cold finger temperature during the (a) first and (b) second on-orbit iterations of the MIDAS experiment.

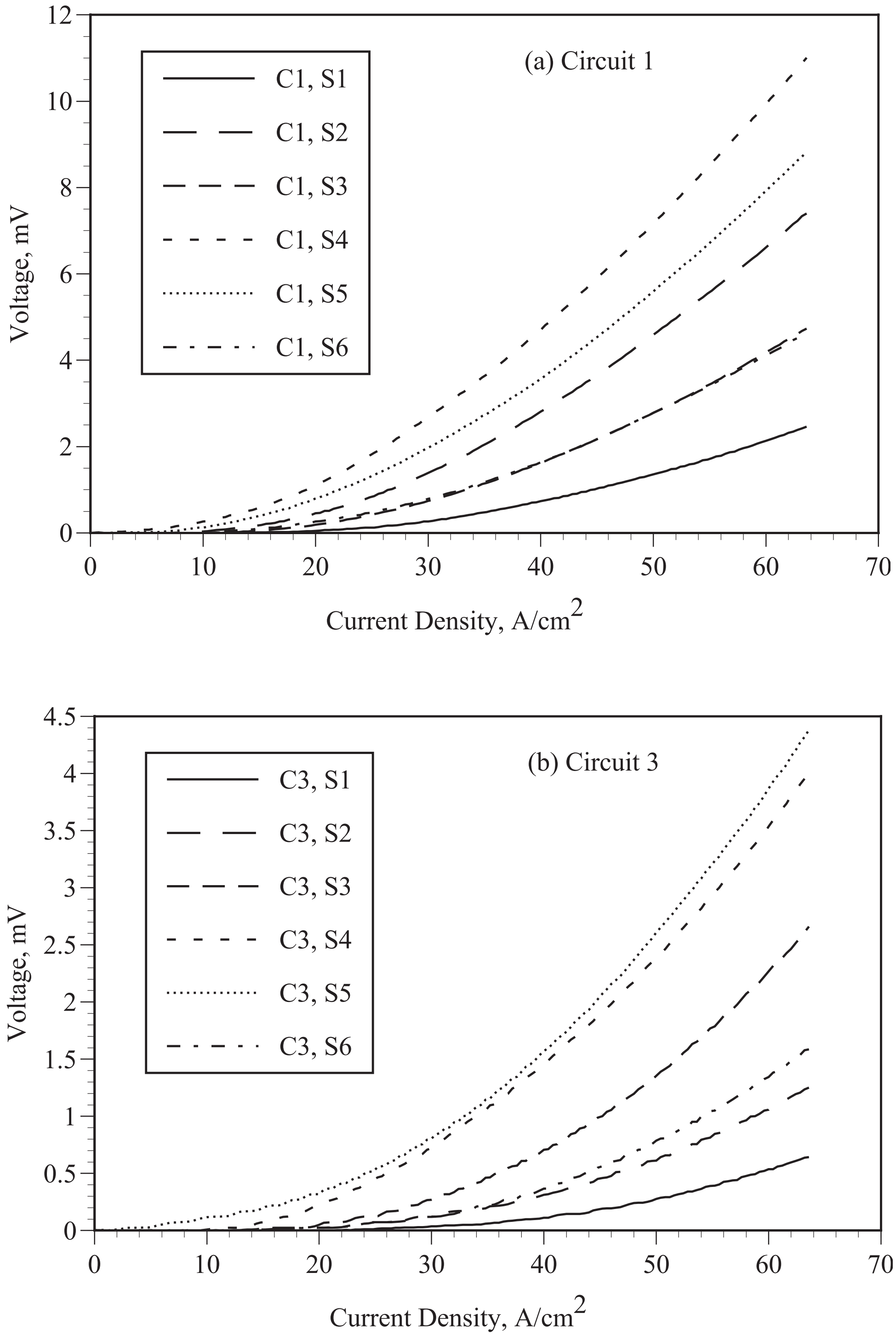

Figure 6. On-orbit current density versus voltage data for the thick film specimens located on circuits 1 (a) and 3 (b).

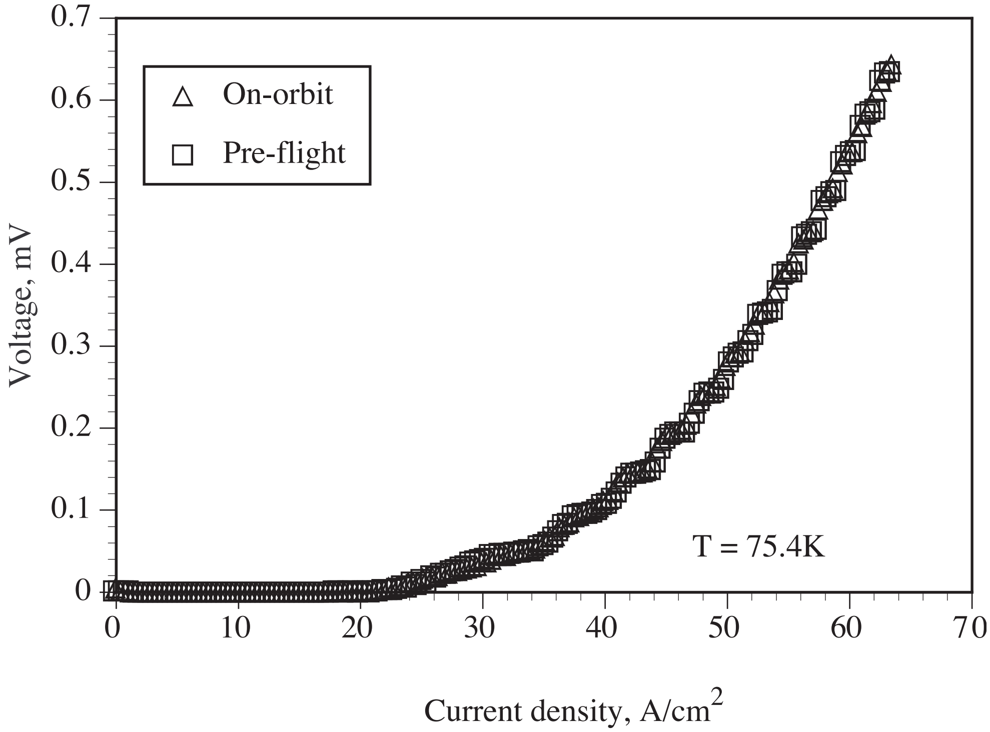

Figure 7. Comparison of the pre-flight and on-orbit J_c data for a typical thick film specimen.

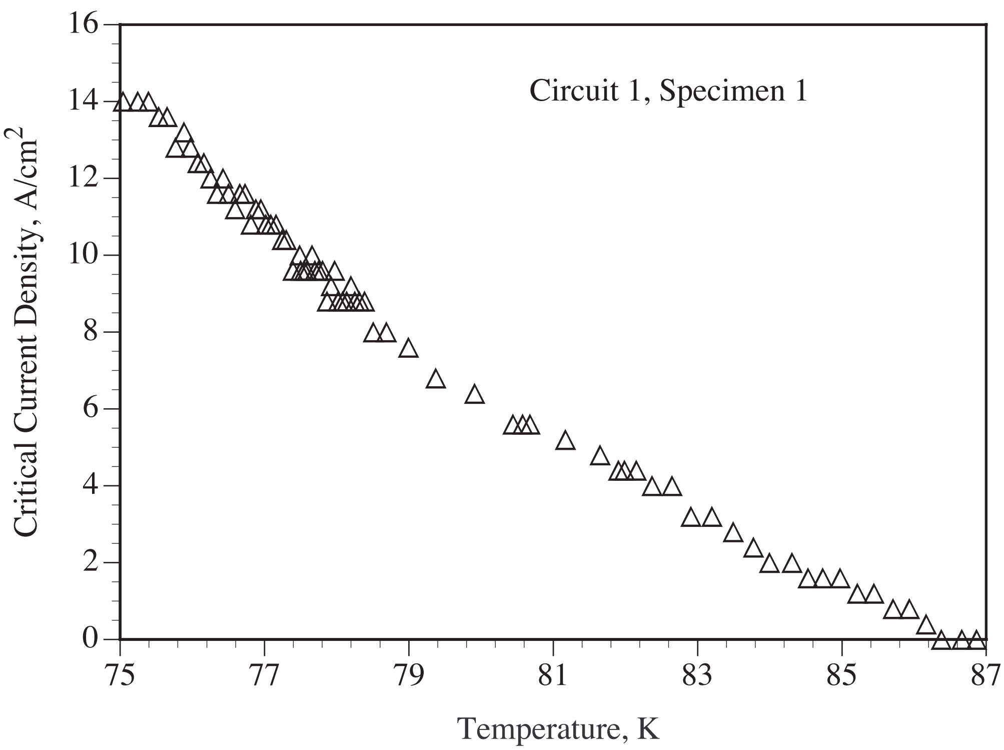

Figure 8. Graph illustrating the effect of temperature on the critical current density of a typical superconductive thick film.

After the specimens were warmed above 87K, measurements of the current versus voltage (I-V) characteristics of the films were continued, although the films exhibited normal resistive behavior (i.e., a linear relationship between current and voltage). In order to evaluate the stability of the films throughout the experiment duration, the I-V data were compared for iterations 2 and 3, during which a constant film temperature of 124K was maintained. During this period, the films exhibited reproducible I-V properties. Figure 9 illustrates the behavior of a typical thick film specimen from day 35 to day 85.

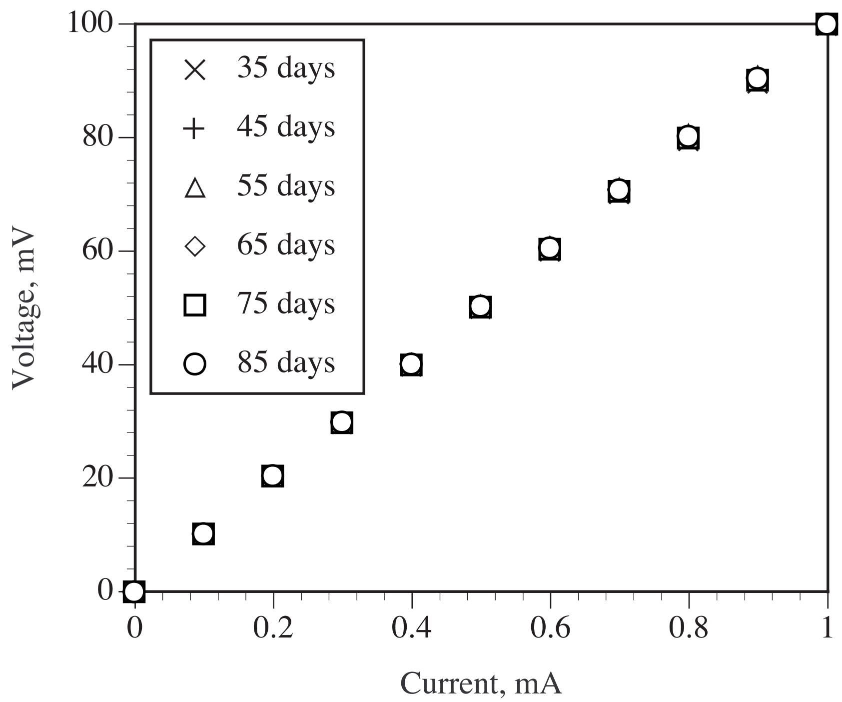

Figure 9. Comparison of on-orbit I-V characteristics obtained at 124K during iterations 2 and 3.

Additionally, the resistance values obtained during these measurements are equal to those acquired during the T_c measurements performed during the initial on-orbit cool-down. At 124K, specimen C1,S1 (illustrated in figure 9) generated 10.2 mV when a current of approximately 0.1 mA was applied. After 85 days on orbit, the same voltage was obtained from this specimen at 0.1 mA during the J_c measurements. These results were further confirmed during the final on-orbit warm-up, performed on day 88, in which the specimen again generated 10.2 mV.

To further evaluate the stability of the J_c properties of the thick films, continuous testing was also done before and after spaceflight by performing accelerated measurement cycles. During these tests, a data set comparable in size to that of the flight data was acquired, although the measurement time interval was reduced to allow the entire data set to be collected over a 4-day period. For the pre- and post-flight measurements, the specimens were evaluated at a constant temperature of 75K, and the films exhibited superconductive behavior as anticipated. The J_c properties of the films were reproducible during these continuous tests. Figures 10a and 10b illustrate the pre- and post-flight performance respectively for one iteration (i.e., data set comparable to 30 days of on-orbit data) for specimen C3, S3. In these figures, the J_c values are provided for each of the 1300 measurements performed during the simulation of one 30-day iteration.

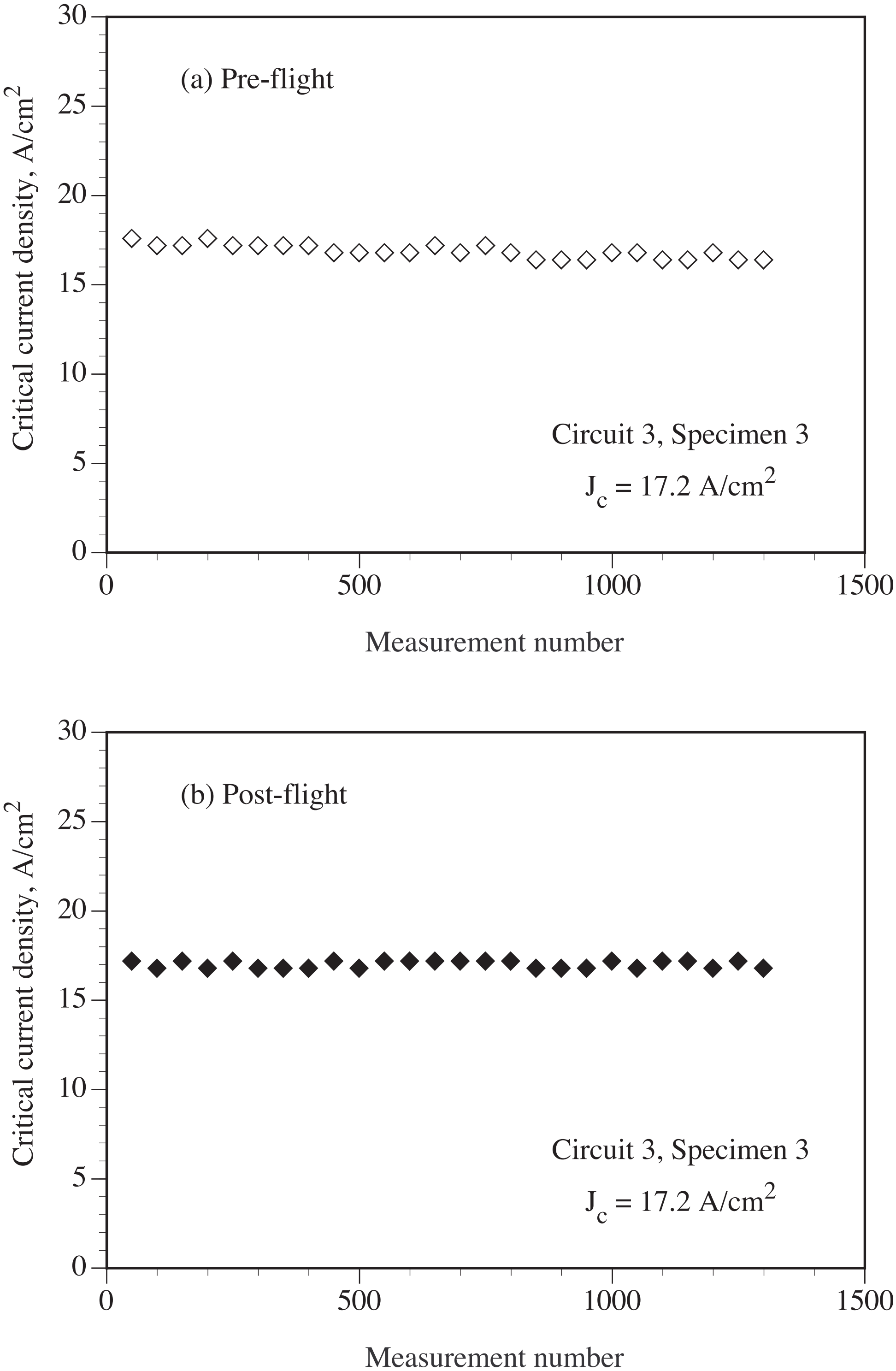

Figure 10. Graph showing the pre-flight (a) and post-flight (b) J_c performance during simulations of one 30-day iteration.

Discussion

The J_c properties of twelve superconductive thick films were successfully measured on the Mir space station as part of the MIDAS experiment. The films exhibited J_c values ranging from 1 to 24 A/cm^2 and demonstrated properties that were comparable to those observed prior to launch. The reproducibility of the ground and flight data indicates that no microcracking or other damage to the films occurred as the result of vibrational stresses encountered during launch. This finding is significant in that it demonstrates the launch survivability of thick film superconductive materials deposited onto polycrystalline ceramic substrates. Moreover, the specimens tested on orbit were integrated with microelectronics circuitry, demonstrating that hybrid devices containing high-temperature superconductors can be fabricated to both operate at cryogenic temperatures and be sufficiently durable for use in spacecraft systems.

Additionally, the on-orbit J_c properties of the films exhibited a strong dependence on film temperature. This result agrees with similar data acquired on the ground for high-temperature superconductors in which the J_c was found to exhibit near-linear variance with temperature when cooled below the T_c (refs. 11 and 12). This finding provides further indication that the on-orbit behavior of the thick films is comparable to that on the ground.

Despite the hardware difficulties encountered during the experiment, the I-V characteristics of the films were measured throughout the 90-day test on Mir. During this time, no degradation or change in the I-V properties was observed. These results indicate that no negative effects on film performance resulted from nearly continuous operation of the circuitry (i.e., J_c measurements), thermal cycling from ambient to 75K, long term maintenance at cold temperatures (e.g., 75 to 125K), operation under vacuum, and operation in a microgravity environment. Many of these conditions will be encountered during space applications of superconductive films. Results from the MIDAS flight experiment indicate that the films should have sufficient durability to withstand these conditions and perform as expected on orbit.

Hooker (ref. 8) found similar results in an investigation of the T_c properties of the $YBa_2Cu_3O_{7-x}$ thick films tested during the MIDAS space experiment. The test specimens exhibited T_c values of approximately 87K when measured both prior to launch and on-orbit. Additionally, the resistance values acquired during the first cool-down on orbit were identical to data measured on the final warm-up (i.e., day 88 of the experiment).

The MIDAS experiment represents the first demonstration that superconductive materials can be fully functional in a space environment. The MIDAS hardware was designed to permit on-orbit evaluation of the films at cryogenic temperatures, allowing the superconductive operation to be investigated during spaceflight. The results are promising for the many space applications considered for high-temperature superconductive materials and alleviate concerns associated with either vibrational stresses encountered during launch or operation in microgravity conditions.

Conclusions

Twelve $YBa_2Cu_3O_{7-x}$ thick film superconductors were evaluated as part of a 90-day experiment on the Mir space station. The films exhibited on-orbit J_c properties of 1 to 24 A/cm^2 at approximately 75K, comparable to properties obtained on the ground prior to launch. As anticipated, the films showed a strong dependence of J_c on film temperature, particularly when close to the superconductive transition temperature of 87K. Additionally, the films demonstrated consistent electrical performance over the 90-days.

The results of the MIDAS experiment demonstrate the viability of employing superconductive thick films in spacecraft applications. No degradation was evident, validating the survivability and performance of the thick films in the space environment. Additionally, the films were integrated into durable microelectronics packages and used in conjunction with conventional electronic components, in a similar fashion as devices required for near-term space applications.

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Screen-printed thick films of the $YBa_2Cu_3O_{7-x}$ high-temperature superconductor were integrated into hybrid microelectronics circuits and characterized on orbit as part of the Materials In Devices As Superconductors (MIDAS) spaceflight experiment. The experiment operated autonomously for 90 days on the Mir space station and acquired electrical data on the superconductive films at temperatures ranging from 250 to 75K. This report describes the on-orbit critical current density, J_c, performance of the $YBa_2Cu_3O_{7-x}$ thick films and compares the flight data with those obtained during pre- and post-flight testing. The results of this investigation show no significant difference between the spaceflight and ground data, indicating that no degradation occurred in the superconductive films due to either vibrational loads experienced during launch or continuous operation in a microgravity environment.

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